

DISSOLUTION OF PRIMARY SOLAR-TYPE ATMOSPHERE INTO THE EARTH'S INTERIOR AND TERRESTRIAL NOBLE GAS EVOLUTION. Sho Sasaki, Geological Institute, University of Tokyo, Hongo, Tokyo 113, JAPAN, sho@geol.s.u-tokyo.ac.jp

When planetary formation proceeds in the presence of the primordial solar nebula, a planet should attract the surrounding solar-type gas to form the primary atmosphere [1]. Because blanketing effect of the atmosphere should delay escape of accretional energy, the planetary surface was in molten state when the planetary mass surpasses Mars' mass, leading to the formation of the extensive magma ocean. Water vapor from the reaction between atmospheric hydrogen and molten silicate or iron oxide would raise the temperature higher by enhancing molecular weight and opacity of the atmosphere [2]. The gas of the primary atmosphere can dissolve into the planetary interior. Specially a large amount of noble gases may be dissolved [3]. Recent detailed measurements of Ne isotopic ratio of mantle-derived materials show that the Earth's interior should have solar-type Ne composition that is different from that of the atmosphere [4]. However, dissolved Ne amount should not be much larger than that of the present atmosphere [5]; the primary atmosphere should have started escaping no later than $M=0.6 M_E$ (M_E being the Earth's mass) [6].

Recently Harper and Jacobsen [7] advocate the presence of the dissolved component of the primary atmosphere from re-estimating the interior He and Ne. They consider that the estimated ^3He abundance of the deep plume source should be explained by dissolution of solar-type noble gas. However, quantitative estimates of dissolution of all noble gases have not been performed. In the present study, we estimate the dissolved noble gas amount from the surface pressure obtained from the numerical analysis of the primary atmosphere, using a previously developed numerical code [6].

Figure 1 shows the change of pressure of the primary atmosphere at the planetary surface (in other words at the bottom of the atmosphere). Calculations were done for constant mass accretion rate $1M_E/10^7\text{yr}$ or $1M_E/10^6\text{yr}$. In reality, the accretion rate should be much lower at the final stage of accretion; if the primary atmosphere existed by the end of accretion, dissolved amount should be 10-100 times larger! An analytic solution ($P \sim M^2$) [6] is also shown for comparison.

Using the obtained pressure, normalized abundances of dissolved noble gases are calculated and shown in Fig. 2. As for Henry's constant of dissolution, we used values for basalt melt by Jambon et al. [8]. Other experiments [9, 10] also give compatible dissolution constants. The higher normalized abundances of lighter gases are due to their larger Henry's constants. The present atmospheric pattern and "planetary" (typical meteorite) pattern are shown for comparison: both are highly fractionated with more depletion of lighter elements from the solar pattern. Therefore, dissolved component of the primary atmosphere can easily

control He and Ne but may not affect gas heavier than Ar. To satisfy primitive ^3He abundance [7], the primary atmosphere should have existed at least by $M = 0.3 M_E$. However, as was discussed previously [6], the existence of primary atmosphere by the end of accretion is not plausible because dissolved Ne amount would be much larger than the present amount. The primary atmosphere should have started escaping in accordance with the dissipation of the solar nebula, probably by the strong ultraviolet radiation from the protosun. Then the atmosphere is replaced by the degassed volatiles from accreting materials whose noble gas has planetary elemental pattern with much lower concentration of He and Ne than the preincorporated dissolved component. The degassed atmosphere mainly of H_2O and CO_2 also enhances the surface temperature by the blanketing effect [11]. But finally atmospheric escape or slower accretion rate may start the surface cooling; solidification of the magma ocean (originally in partially molten state in the deeper region) extracts the dissolved volatile. Some fraction of the present atmospheric component should have degassed in the course of the magma ocean cooling.

As for Ne trapped in accreting solids, two types of isotopic components can be considered. Assuming Ne-A ($^{20}\text{Ne}/^{22}\text{Ne} \sim 8.2$) for the trapped Ne, the present atmospheric Ne is explained by the mixing between the accreting Ne and dissolved Ne which should be degassed from the interior during solidification of the magma ocean. On the other hand, if the accreting Ne has Ne-Q ($^{20}\text{Ne}/^{22}\text{Ne} \sim 10.7$), the air Ne should be explained by mass fractionation along with hydrodynamic escape of the atmosphere [12]. These two cases are shown in Fig. 3.

Recent studies show neon isotopic ratio in the mantle should have two types of end members: MORB type and Plume type [4, 13]. Both types can be explained by solar-type Ne with $^{20}\text{Ne}/^{22}\text{Ne} \sim 13.0$ plus nucleogenic ^{21}Ne (Fig. 3). As for He and Ar, we can also consider MORB and Plume components both of which have evolved from the initial component (dissolved He and trapped Ar) (Fig. 4). The high $^{40}\text{Ar}/^{36}\text{Ar}$ of the plume component is recently proposed by Matsuda and Marty [14]. The most simple model is that MORB component represents the present upper mantle whereas Plume component corresponds to the lower mantle. In the course of this model, the difference of $^{21}\text{Ne}/^{22}\text{Ne}$ in Fig. 3 can be explained by remaining Ne concentration if both source regions have similar abundances of U and Th that supply alpha particles in the reaction $^{18}\text{O}(\alpha, n)^{21}\text{Ne}$. The difference of $^4\text{He}/^3\text{He}$ and $^{40}\text{Ar}/^{36}\text{Ar}$ in Fig. 4 would also reflect the relatively noble gas rich (or less-degassed) lower mantle.

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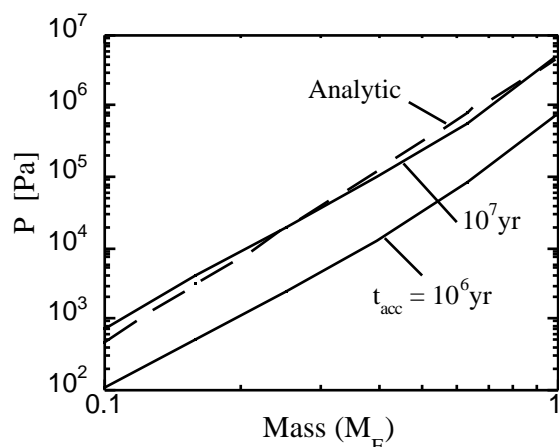


Fig. 1 Pressure of the primary atmosphere at the surface during planetary accretion. Dust/gas mass ratio in the atmosphere is 3×10^{-3} and dust size is 10^{-5} [m]. Because evaporation of surface materials would supply solid materials to the atmosphere, the assumed high dust abundance is reasonable. (Lower dust abundance or larger dust size would result in higher surface pressure.) Calculations were done for constant mass accretion rate $1M_E/10^7$ yr and $1M_E/10^6$ yr. Numerically obtained trend matches well analytic solution [6].

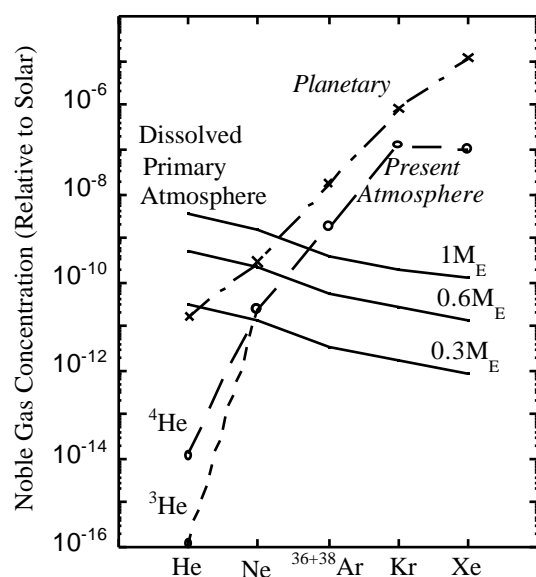


Fig. 2 Dissolved amount of noble gas for three cases of the duration of the primary atmosphere. Three masses denote the Earth's mass when the solar-type atmosphere escapes. Mass accretion rate is $1M_E/10^7$ yr. We use solubility data by Jambon et al. [8]. The "planetary" elemental pattern denoting primitive condensed solid from the nebula and the pattern of the Earth's atmosphere are shown for comparison. Note that Harper and Jacobsen [7] estimated ^3He abundance of the Plume source to be as high as planetary He.

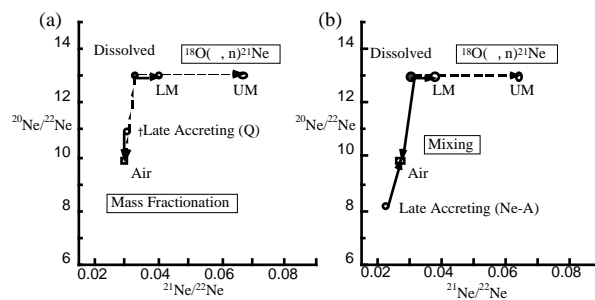


Fig. 3 Model of evolution of Ne isotopes. LM and UM denote assumed end members of Plume Ne and MORB Ne sources. Observed data are mainly explained by mixing between Air Ne and both end members. Both LM and UM Ne evolve from the dissolved component of the primary atmosphere by the addition of nucleogenic ^{21}Ne . (a) Air Ne is explained by the mixing between dissolved Ne and Ne-A. (b) Air Ne is explained by mass fractionation from dissolved Ne (and phase Q type Ne).

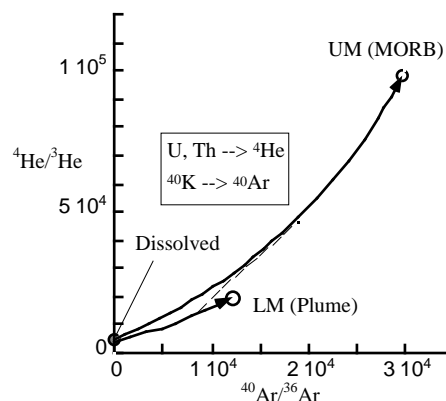


Fig. 4 Model of evolution of He and Ar isotopes in the Earth's interior. The end member of Plume source corresponds to X component of Matsuda and Marty [14]. Note that this diagram is simplified and in reality neither UM nor LM is in a closed system: penetrating plumes and subductions may contaminate UM and LM each other and successive melt extraction and degassing may modify abundance of U, Th, K and noble gases, especially in UM.

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